DEVELOPMENT OF A WIDEBAND ACOUSTIC RECORDING TAG TO ASSESS THE ACOUSTIC BEHAVIOR OF MARINE WILDLIFE

Final Report

Prepared for:

Office of Naval Research
Code 32 – Marine Mammals & Biological Oceanography Program
One Liberty Center, Room 1068
875 North Randolph Street
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GREENERIDGE SCIENCES, INC.

1411 FIRESTONE ROAD • SANTA BARBARA, CALIFORNIA 93117 • TEL/FAX 805 967-7720

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William C. Burgess, Principal Investigator

Greeneridge Sciences, Inc.
1411 Firestone Road
Santa Barbara, California 93117
tel: 831-335-9600
fax: 805-967-7720
email: burgess@greeneridge.com

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ABSTRACT

Instrumentation capable of monitoring free-ranging marine animals is an essential foundation for research on sound and marine wildlife. Acoustic recording tags, in particular, offer the capability to record a subject's acoustic exposure as well as its vocalizations and kinematics, providing a complete picture of a wild animal's acoustically-related behavior. In 2006, the Office of Naval Research (ONR) initiated support to Greeneridge Sciences to expand the capability of the first and only commercially-available broadband acoustic recording tag, the Bioacoustic Probe, to record high-frequency echolocation vocalizations of beaked whales and other odontocete species. The resulting effort increased the design's maximum sampling rate from 20 kHz to 232 kHz and its maximum storage capacity from 1 GB to 8 GB (64 GB if battery limitations are neglected). USB flash-drive technology replaced infrared transfers for data offloading, speeding offload by a factor of 60 from 17 MB/hour to 1 GB/hour. Other improvements included 3D tilt and 3D compass to support more detailed study of kinematic behavior. The new wideband recorder was announced for commercial sale in January 2009 as the Acousonde™ 3A. Finally, a thorough redesign of the Bioacoustic Probe's shape prepared the way for a future cetacean tag that integrates attachment, flotation, and retrieval systems in a single hydrodynamic package. Tests of a mechanical sample of this integrated tag indicated the need to further reduce its size. The integrated tag, to be called the Acousonde™ 3B, is being revised for planned release in 2010.

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PREFACE

The author wishes to thank Mr. Pat Dexter of Dexter Engineering, who since 2000 has consulted extensively on the mechanical design and fabrication of the Bioacoustic Probe and Acousonde acoustic recording tags. The solid “feel” and reliability of the tangible results of this project owe greatly to his attention, experience, persistence, enthusiasm, and generosity. Worthy of profound gratitude also is Mr. Joseph Olson of Cetacean Research Technology, who through the many ups and downs of this work always had reassurance and sound advice to offer. Mr. Olson designed the attachment and flotation systems used by many Bioacoustic-Probe customers, without which a good deal of cetacean data would never have been acquired. Mr. Dexter and Mr. Olson both contributed heavily to the latest mechanical design, begun under this contract and still being refined, that incorporates attachment and flotation with the electronics in a single hydrodynamic package.

Mr. Rob Cosaro of NXP Semiconductors showed this effort the utmost in generosity, offering documentation, example code, and to the extent possible, engineers’ time, despite our tiny size relative to other customers. It is a rare benefit and privilege to speak with the designers of one’s microprocessor. Meanwhile Mr. John Zsori of Corporate Engineering Services laid out the twelve-layer circuit boards with dedication and responsiveness.

Within Greeneridge Sciences, Dr. Charles Greene, president of Greeneridge, lent complete support to this effort, ensuring that it had all the resources it needed. It is impossible to overstate the contributions of Ms. Debra Martinez, Greeneridge accountant, who shouldered much of the administrative load and who was always glad to help even with the shortest of notice.

Dr. Robert Gisiner, formerly of the Office of Naval Research (ONR), initiated ONR support for this effort as well as for development of the original Bioacoustic Probe. Our current ONR program manager is Dr. Michael Weise.

1 INTRODUCTION

The Navy faces increasing regulation due to the potential impact of its underwater sounds on protected marine wildlife. The need to limit acoustic impacts on protected species potentially affects all at-sea Naval activities and research, including sonar operations, oceanographic studies, live-fire exercises, ship-shock tests, and Naval test ranges. To mitigate acoustic impacts, operations may be moved, modified, delayed, suspended, or canceled. Unfortunately, the necessity and effectiveness of these mitigation measures for most protected species remains unclear, because in most cases these species' acoustic sensitivities have not been adequately quantified.

To characterize acoustic sensitivities for a species challenges us both to make representative measurements and to do so with sufficient sample size. Research animals in captivity form a limited sample set that cannot always be appropriately extrapolated to wild populations; but in the wild, most marine species spend the majority of their time submerged and out of sight of researchers. Thus instrumentation capable of monitoring free-ranging marine animals is an essential foundation for research on the relationship between sound and marine wildlife.

One of the most promising technologies for acoustic investigations of marine animals is that of acoustic recording tags (*Fletcher et al.*, 1996; *Burgess et al.*, 1998; *Madsen et al.*, 2002; *Johnson and Tyack*, 2003). Attached to a marine animal, acoustic recording tags quantify acoustic stimuli experienced by the subject, acoustic emissions produced by the subject and by neighboring animals, and potentially associated characteristics of the subject's behavior over a period of hours to days. These accurate stimulus and response data enable researchers to assess marine animals' sensitivity to sound on an individual basis and in a natural environment.

1.1 THE BIOACOUSTIC PROBE: SUCCESSES AND LIMITATIONS

Between 1999 and 2003, under support from Office of Naval Research (ONR) contract N00014-C-99-0170, Greeneridge Sciences, Inc., developed the first and only commercially-available broadband acoustic recording tag, the Bioacoustic Probe (Figure 1). By the time the Bioacoustic Probe was discontinued in 2007, forty-three units had been built for the animal-bioacoustics and underwater-acoustics research communities. The instruments have been attached to five species of whales, to northern fur seals (Figure 2), and to manatees, and have been implanted in a blacktip reef shark. They have been deployed as fixed autonomous recorders, as elements in arrays, and on a prototype underwater glider (Figure 3). Table 1 details these and other applications and lists representative references.

As the application community for the Bioacoustic Probe grew, so did requests for additional capabilities. These calls came especially from those interested in:

- **Beaked whales**, who appear to be especially sensitive to certain military-sonar sounds and whose echolocation pulses appear only to be detectable at frequencies above 20 kHz (*Johnson et al.* 2005);

Figure 1. The Bioacoustic Probe attached to a humpback whale. Greeneridge Sciences' original acoustic recording tag, developed under contract to ONR during 1999–2003 and discontinued in 2007 (photograph courtesy John Calambokidis, Cascadia Research).

Figure 2. Northern fur seal with Bioacoustic Probe. One of several subjects fitted with Bioacoustic Probes at the Pribilof Islands in August 2004 by Dr. Stephen Insley of the University of California at Santa Cruz. *(Photograph by Stephen Insley)*

Figure 3. A prototype autonomous glider during initial sea trials. The "Liberdade" class of glider, developed with ONR support at the Scripps Institution of Oceanography, incorporated four Bioacoustic Probes to gather attitude and acoustic data during initial trials in April 2004.

- **Quick turnaround of instrumentation**, in which data from just-recovered tags are offloaded and the tags immediately returned to service;
- **More comprehensive kinematic measures** such as 3D heading and full 3D orientation; and
- **Array applications** obtaining several gigabytes of data across multiple recorders during a period of a few hours or days.

These new applications illustrated the growing enthusiasm for acoustic-recording-tag technology. Fundamental limitations in the Bioacoustic Probe's electronics, however, prevented its use in these applications. In particular, the aging 68000-class microprocessor at the heart of its design was not capable of supporting sampling rates greater than 20 kHz, and the low-power capabilities of the entire 68000 series had been eclipsed by those of newer microprocessor architectures. Finally, in 2007, manufacturers of the microprocessor and data-storage unit used in the Bioacoustic Probe discontinued these products and the design reached the end of its useful life.

Besides its hardware and software limitations, when used as a cetacean tag the Bioacoustic Probe suffered from the bulky nature of the total tag package (Figure 1). Although the core cylindrical electronics assembly was small and hydrodynamic, once integrated with suction cups and flotation for cetacean attachments it became ungainly to attach and its high profile and non-hydrodynamic outline incurred less-than-ideal drag. This drag led to shorter deployment lifetimes and higher flow noise in the acoustic record. Higher levels of drag may also have been felt more keenly by subjects to which the tag was attached, with potential effects on subject behavior.

TABLE 1. Bioacoustic-Probe customers as of January 2010.

Customer	Topic & references*	Sponsor
Dr. Whitlow Au *Hawaii Institute of Marine Biology*	Humpback whales	Sea Grant
Mr. John Calambokidis *Cascadia Research* Dr. John Hildebrand *Scripps Institution of Oceanography* Dr. Erin Oleson *NOAA Fisheries*	Blue/fin/humpback whales *Oleson et al.*, 2007 *Goldbogen et al.*, 2006	SERDP CNO N45
Dr. William Chadwick *Oregon State University* Dr. Haru Matsumoto *NOAA PMEL*	Deep-sea hydrothermal-vent monitoring *Chadwick et al.*, 2008	NOAA
Dr. Chip Deutsch *Florida Fish & Wildlife*	Florida manatees	State of Florida
Dr. Gerald D'Spain *Scripps Institution of Oceanography*	Experimental underwater gliders *D'Spain et al.*, 2005	ONR 321OE
Dr. Stephen Insley *Hubbs-SeaWorld Research Institute* *University of California, Santa Cruz*	Northern fur seals *Insley et al.*, 2007	NOAA ONR 322
Dr. Bruce Mate *Oregon State University*	Sperm whales	MMS
Dr. Carl Meyer & Dr. Kim Holland *Hawaii Institute of Marine Biology*	Blacktip reef sharks *Meyer et al.*, 2007	European Commission, NOAA
Dr. James Miller *University of Rhode Island*	Autonomous underwater vehicles	ONR 321OA
Dr. Brandon Southall *NOAA Ocean Acoustics Program*	NOAA-supported applications	NOAA
Dr. Dajun Tang *University of Washington*	Seafloor geoacoustics and geophysics *Tang*, 2005; *Leifer and Tang*, 2006	ONR 321OA, NOAA
Dr. Aaron Thode *Scripps Institution of Oceanography*	Field-configurable hydrophone arrays *Thode et al.*, 2006 Sperm whales *Thode*, 2004	ONR 321OA

*Citations are intended to be representative only and do not constitute an exhaustive listing.

1.2 DEVELOPING A WIDEBAND ACOUSTIC RECORDING TAG: THE ACOUSONDE™

In March 2006, ONR initiated support to Greeneridge Sciences to redesign the Bioacoustic Probe. The redesign aimed principally to support the higher sampling rates necessary to capture odontocete echolocation clicks. Extended objectives focused on more detailed measurement of kinematics, specifically 3D attitude and compass heading. The resulting instrument, with completely replaced electronics and software but with a similar mechanical configuration, was announced in January 2009 as the Acousonde™ 3A.

In addition to the electronic and software overhaul, ONR also supported a thorough review of the Bioacoustic Probe's mechanical design for more hydrodynamic application to cetaceans. The effort resulted in a completely new "monolithic" mechanical design that integrated electronics, attachment, flotation, and retrieval gear in a single hydrodynamic package. Tests of a mechanical sample of this monolithic design after contract completion, however, showed that it was still too bulky and that further design was necessary to reduce its size. Announcement of the monolithic configuration, to be called the Acousonde™ 3B, is expected in the summer of 2010.

This report details the Acousonde's electronic, software, and mechanical development from project inception in March 2006 to the end of contract support in December 2008. While the trademark "Acousonde" was not announced until January 2009, it is used throughout this report to refer to the new design. The earlier trademark "Bioacoustic Probe" will refer specifically to the instrument's prior generation.

1.3 LONG-TERM GOALS

The scientific need for large sample sizes with diverse species guided every aspect of the Bioacoustic Probe and Acousonde projects. The projects' core philosophy is that, as with any empirical science, large sample sizes are imperative for confidence. To maximize sample size requires the identification and elimination of barriers to large-scale data acquisition. We seek to address these barriers with the following long-term design goals:

- **Ease of use.** Reduced training requirements mean that deployment opportunities will not be limited by the availability and affordability of specialized personnel.
- **Convenience.** Instruments that can be quickly transported and deployed with a minimum of preparation and care are more likely to catch brief or unexpected opportunities.
- **Flexibility.** Different species have different measurement needs. Broad design for use with a variety of species ensures application diversity. Identifying and addressing the needs of fields besides protected-species research, such as geoacoustics, robotics, and shipbuilding, not only leverages ONR's original investment but also supports the project's transition to self-sustaining status.
- **Reliability.** Broken instruments do not acquire data.
- **Manufacturability.** It may be necessary to fabricate large numbers of the instrument.

- **Commercial availability.** Commercial availability ensures that all science organizations have access to the technology independent of their internal engineering capability or their research affiliations.

1.4 TECHNICAL OBJECTIVES

1.4.1 Primary data acquisition goals

The development's technical objectives fell into three broad categories: primary data-acquisition goals, extended data-acquisition goals, and mechanical goals. Table 2 compares the original Bioacoustic-Probe ("B-Probe") characteristics with the primary and extended objectives and the latest Acousonde specifications as of January 2010.

The primary objective was to create an acoustic recording tag suited for use with echolocating odontocetes. This objective required a tenfold increase in the Bioacoustic Probe's maximum sample rate, from 20 kHz to about 200 kHz, so that the full spectrum of beaked-whale echolocation clicks from 25 kHz to 75 kHz (*Johnson et al.*, 2005) could be recorded. Furthermore, to be of any use, this dramatic increase in sampling capability required corresponding increases in both data capacity and data offload speed. These three enhancements—higher sampling rates, greater storage capacity, and faster data-offloading speed—formed the core of the design effort.

1.4.2 Extended data acquisition goals

While the effort focused on the primary objective of wideband acoustic capability, it also pursued several extended objectives to the degree that time and support allowed. These extended objectives included better support for kinematic research with the incorporation of 3D attitude and compass-heading sensors, and faster sampling rates for all auxiliary (non-acoustic) sensors.

1.4.3 Mechanical goals: a monolithic & hydrodynamic cetacean tag

To minimize development time, the Acousonde's initial mechanical design (the Acousonde 3A) closely resembled that of the Bioacoustic Probe (Figure 4). Its battery housing, however, required modification due to an increased depth target (3000 m instead of 2000 m) and the need for a larger battery.

While inheriting the Bioacoustic Probe's mechanical design allowed construction of the first Acousonde units to take place sooner, it was recognized that this design was less than optimal for cetacean attachments owing to the bulk and drag of the total assembled package. As a result, the project adopted a final objective of redesigning the tag's shape and weight distribution as part of an integrated, "monolithic" tag assembly (the Acousonde 3B) specifically for use with cetaceans. The mechanical redesign took into account the following requirements:

TABLE 2. Original characteristics, primary and extended design goals, and latest specifications.

Capability	B-Probe	Goal	Ext. Goal	Acousonde	Units
Acoustic capabilities (one channel at a time)					
Hydrophones available	1	1		2	
Resolution	16	16		16	bits
Max sample rate	20	200		232[a]	kHz
Max data frequency (low power)	7.4	14.0		9.3	kHz
Max data frequency (high speed)	n/a	100		100[b]	kHz
Storage capacity	1	8		8–64[c]	GB
Lifetime at 2 kHz	2.9	23		22[d]	days
Lifetime at 20 kHz	7	56		53[d]	hours
Lifetime at max rate	n/a	5.6		4.6[d]	hours
Auxiliary sensors					
Resolution	16	12	16	24	bits
Max sample rate	4	4	32	60[e]	Hz
Depth calibration	linear	linear	nonlinear	linear	
Attitude	2D	2D	3D	3D	
Compassing	no	no	yes	yes	
Power and Communication					
Primary lithium battery size	1/2 AA	AA	1/2 AA	A	
Commanding method	Palm+IR	Palm+IR		Palm+IR	
Data offload technology	IR	Fast IR	Very Fast IR	USB	
Time to offload 1 GB	55	1	0.25	1	hours
Time to offload 8 GB	n/a	8	2	8	hours
Mechanical					
Max depth	2000	3000		3000[e]	m

[a]As of January 2010, 232 kHz tested only for burst sampling, not continuous
[b]High-frequency antialias filter down 3 dB at 42 kHz, 22 dB at 100 kHz
[c]Electronics support up to 64 GB, but battery limitations suggest 8–32 GB maximum usable
[d]Assuming 7.7×10^9 bytes of formatted acoustic storage
[e]Predicted by design, not yet tested

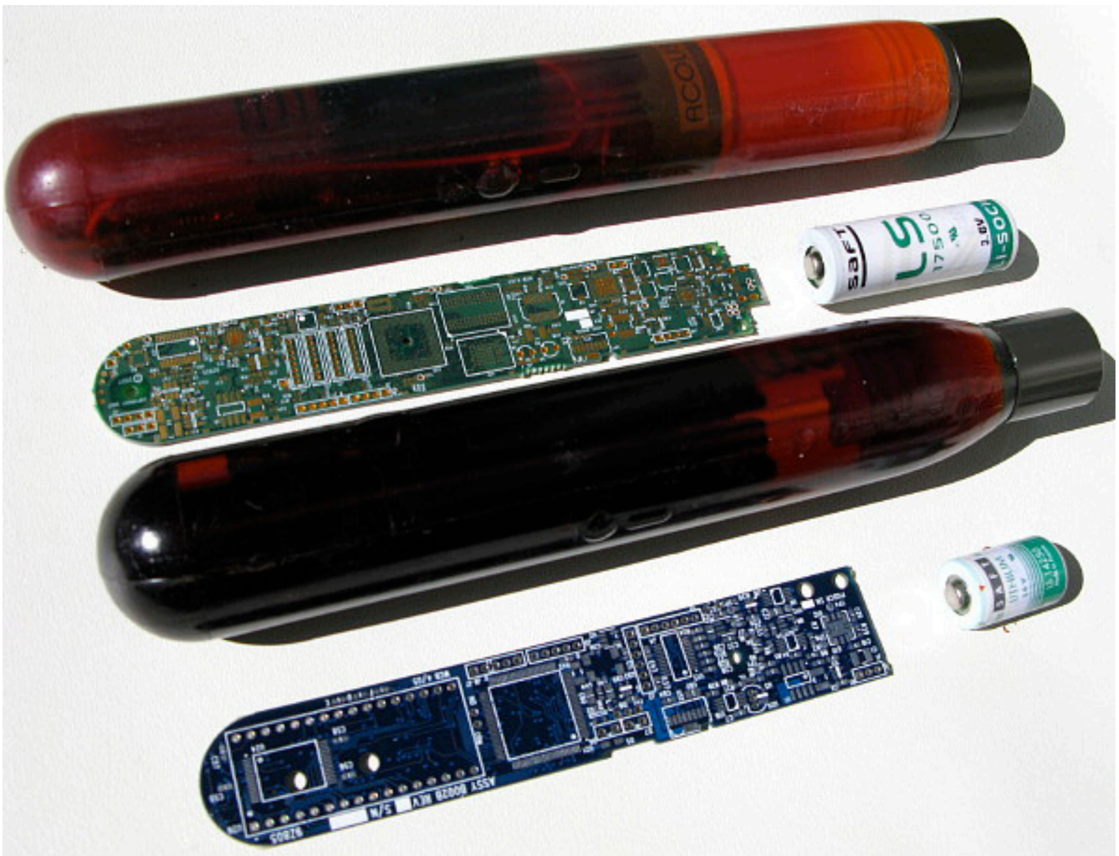

Figure 4. Comparison of Acousonde 3A and Bioacoustic Probe mechanical designs. To minimize mechanical development effort for the first Acousonde units, the Acousonde 3A (top) inherited the Bioacoustic Probe's basic external design (bottom). The circuit boards are the same width and nearly the same length; the Acousonde, however, requires an A-size primary lithium battery as opposed to the Bioacoustic Probe's 1/2-AA-size battery.

- **Hydrodynamic.** Designing the integrated package as a whole to be hydrodynamic will increase deployment life and reduce flow noise.
- **Buoyant with the correct orientation when afloat.** The integrated package must not only float, but float in such a way that the VHF retrieval beacon is consistently exposed to the air.
- **Small and robust.** The package must be compact and light enough to attach, while strong enough to withstand the attachment process.
- **Rapid to prepare in the field.** The package should require minimum time in the field to assemble and prepare for deployment.
- **Configurable.** The flotation and attachment components should be replaceable without requiring alteration of the core electronics unit.
- **Releases with both active and redundant mechanisms.** There should be a way to time the tag's release from a subject, and an additional redundant release as a backup.

1.5 KEY WORDS

Acousonde, Bioacoustic Probe, Compact Acoustic Probe, hydrophone tag, bioacoustic tag, acoustic recording tag, acoustic data logger, marine mammal, acoustic dosimetry, sound exposure, noise, underwater acoustics, protected species.

2 TECHNICAL APPROACH

The overall concept of the Acousonde mirrors that of the Bioacoustic Probe (Figure 4). The design consists of a pressure-tolerant single-board computer and data acquisition electronics sealed in a robust urethane along with a pressure vessel housing a field-replaceable battery. Commanding takes place via an infrared optical link to avoid external connectors and cabling. Figure 5 compares the Acousonde's 2007 conceptual design (a) with its first full realization in January 2009 (b).

2.1 ELECTRONIC DESIGN

2.1.1 Microprocessor and operating memory

When development began on the new instrument, the easiest technical approach would have been to reuse the Bioacoustic Probe's design to the greatest extent possible. Without adopting more recent technology, however, there was no way to increase sample rate, storage capacity, and offload speed tenfold while keeping size and power demands nearly constant. In particular, the capabilities and power requirements of the Bioacoustic Probe's 16-MHz 68EZ328 microprocessor, and indeed those of the entire Motorola 68000 family, fell far behind those of more recent architectures.

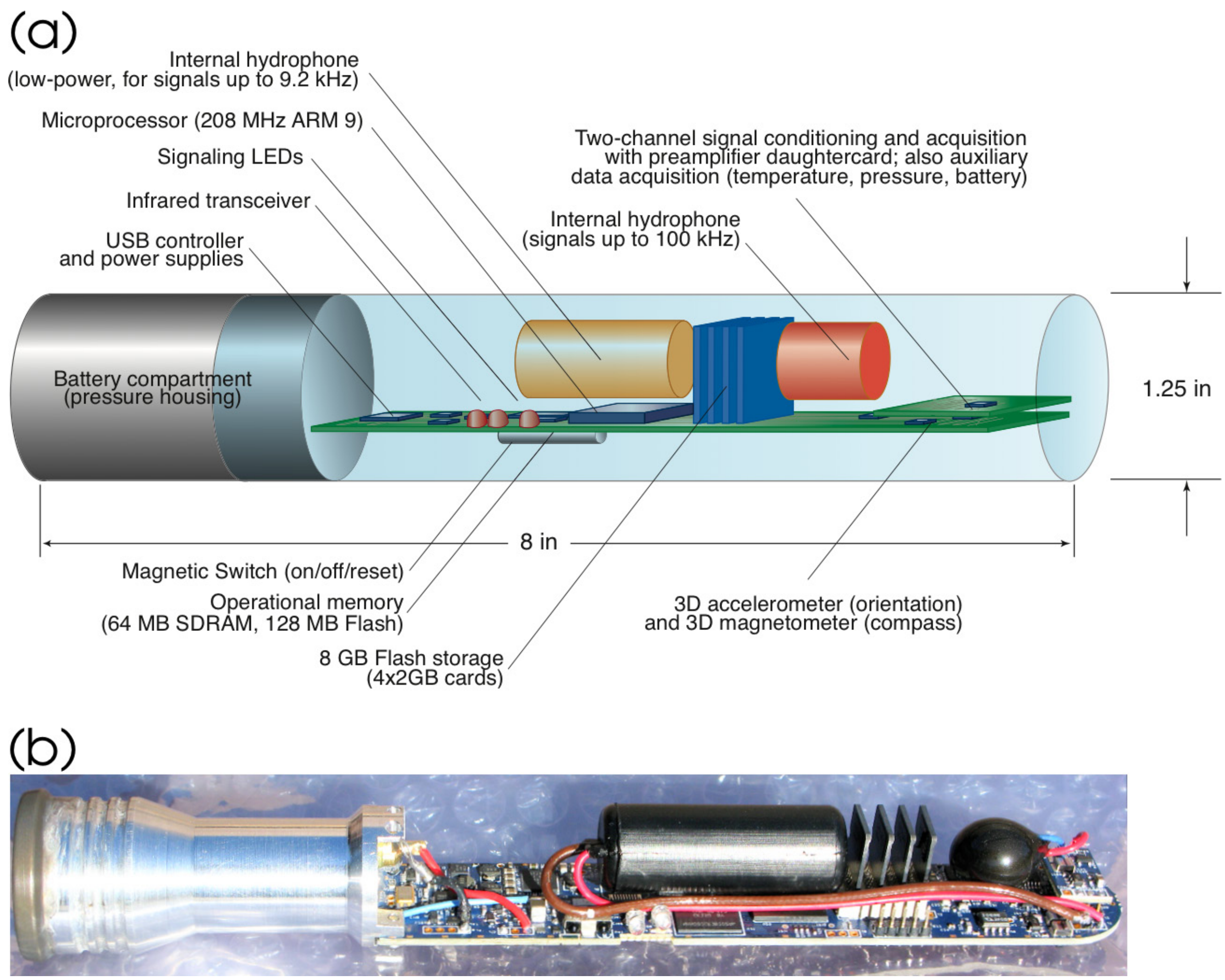

Figure 5. Comparison of the 2007 conceptual design (a) with its first full realization in January 2009 (b) prior to encapsulation. Not visible in the photograph is the USB connector, located on a tongue of the main electronics board that protrudes into the battery housing so as to be accessible through the housing after urethane encapsulation. The USB tongue is however visible on the Acousonde 3A circuit board shown in Figure 4.

Therefore, as the project's first step, the ARM processor architecture was selected to replace the aging 68000 architecture. ARM processors (or "cores") are designed for low-power portable environments; they are built into microprocessors available from many vendors, diminishing sole-source concerns; and they enjoy wide popularity, with abundant example code and many low-cost development tools available.

The new design uses the 208-MHz NXP LPC3180 microprocessor with an ARM9 core. This system-on-chip was originally developed for use with cell phones and features a number of state-of-the-art power-saving technologies, particularly dynamic core-voltage capability and support for low-voltage memories. The LPC3180 also contains a vector-floating-point (VFP) coprocessor, allowing it to perform signal processing rapidly without excessive power consumption. The current software does not use the VFP but it is available for future applications.

A drawback of the LPC3180 is its limited on-board memory: only 64 kB of SRAM and no non-volatile memory. This made external memory necessary, so the design added 64 MB of external SDRAM and 256 MB of external Flash memory. Only a small portion of the 256 MB Flash chip is reserved for the boot loader and operating system; most of it is available for data storage.

2.1.2 Power supplies

To achieve optimum power conservation, the LPC3180 requires five independent power supplies at voltages ranging from 0.9 to 2.7 V. Together with three separate power systems for the data acquisition electronics, the Acousonde needs eight power supplies in total (Table 3). Because dynamic power consumption varies with the square of the applied voltage, lowering operating voltages significantly improves battery life; therefore the lowest possible voltages were applied throughout the design.

2.1.3 Data storage

The Acousonde 3A stores acoustic data in a bank of four micro secure-digital (MicroSD) cards. The presence of an SD-card controller on the LPC3180 simplified the electrical interface; this controller, however, was designed for use with a single card. Additional multiplexing circuitry was added to extend the controller's capability to four cards (with only one card powered and accessible at a time).

The use of MicroSD cards allows future units to take advantage of increasing card capacities. For example, at project inception, MicroSD cards were available in no more than 2 GB sizes and the Acousonde's bank of four cards thus allowed a maximum capacity of 8 GB. As of this writing, MicroSD cards are available in sizes up to 16 GB, translating to a maximum capacity of 64 GB with no change to the Acousonde electronics or software. Data acquisition is highly unlikely ever to go past 32 GB in a single deployment, however, due to power drain and battery size.

TABLE 3. Acousonde power supplies.

Function	Voltage	Supply type	Comment
LPC3180 ARM9 processor core	0.9–1.2	switching	Dynamically adjustable
LPC3180 system clocking	1.2	linear	
LPC3180 real-time clock	1.2	linear	Battery backed-up
LPC3180 memory controller and memories	1.8	switching	
LPC3180 other controllers and peripherals	2.7	switching	
Pressure-transducer and compass bridges	1.5	linear	
Analog signal conditioning	2.8	linear	
Compass conditioning	15.0	switching	Active briefly on isolated occasions

2.1.4 Data offloading

Original plans called for data offloading via 4 megabit per second (Mbps) infrared or, ideally, 16 Mbps infrared. Infrared data offload would rely on well-tested software used in the Bioacoustic Probe and minimize additional development effort for the offloading process.

Unfortunately, after extensive design around a 16 Mbps infrared controller from SigmaTel (now part of Freescale Semiconductor), SigmaTel discontinued the part and no equivalent replacement was available. This forced a significant design change from infrared to USB data transfer by simulating a USB flash drive.

Although the mid-effort design switch from infrared to USB set the project back severely, it may have been a blessing, as USB technology will be more broadly compatible and will be better positioned for future improvements in data offload rates.

The USB connector is located inside the battery housing and is accessible when the battery is removed. Connecting the Acousonde with a personal computer via USB cable provides power to the Acousonde, which subsequently boots as an external USB flash drive. Data files are then accessible for opening or copying as with any such drive.

2.1.5 Commanding

Field commanding for animal tags may take place in conditions that are cold, cramped, wet, windy, dark, dirty, rocking, and rushed. The traditional commanding method for embedded-microprocessor systems—a notebook computer and commanding cable—suffers in such environments. Risks include not only damage to the notebook computer, but also contamination or loss of the cable, any of which would end operations until replacements could be located.

To maximize convenience and reliability in field conditions, the Bioacoustic Probe used a small handheld Palm-compatible personal digital assistant (PDA) to accept user commands via a graphical user interface (GUI). The commands were then transmitted optically to the Bioacoustic Probe, avoiding the need for cabling. The success of this approach over several years of field work led to its continuation with the Acousonde (Figure 6).

The use of optical commanding obviates the need for any electrical connection to be expressed at the outside surface of the instrument. Without exposed electrical contacts the instrument requires less care and can withstand harsh conditions more robustly.

2.1.6 Hydrophones and primary data acquisition

Two hydrophones

Early concepts anticipated that a single hydrophone would suffice for the entire design frequency range (up to 100 kHz); however, the higher amplification, or gain, required for high-frequency signals relative to low-frequency signals could not be accommodated with this approach.

Recording higher frequencies requires higher gain for two reasons. First, higher frequencies attenuate more rapidly during propagation than lower frequencies. Without greater gain than one might use for low frequencies, signals from a distance, such as echoes of the subject's echolocation clicks or the clicks of other odontocetes, might be too weak to be recorded. Second, antialias filters roll off (i.e., block unwanted signals above the filter cutoff) more gradually as a function of linear frequency at higher frequencies. A typical compromise design sets the antialias cutoff at a lower frequency and tolerates increasing antialias attenuation within the desired passband, rather than setting the cutoff closer to the

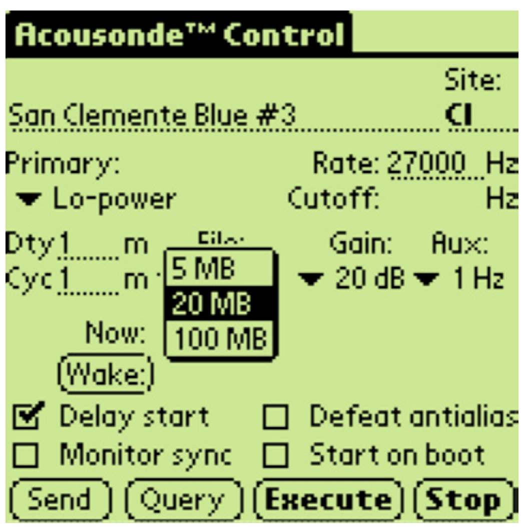

Figure 6. PalmOS graphical user interface for commanding the Acousonde. The user provides a title for the recording, a two-letter site code ("CI" in this hypothetical example as an abbreviation for San Clemente Island), and the desired sample rate and gain. Other options include the choice of file size (the popped-up menu here), primary signal source (the low-power hydrophone system is selected here), and the ability to delay start of recording to some time in the future.

top of the desired passband and suffering excessive aliasing from signals above it. Higher gain compensates for this attenuation of high frequencies within the passband.

While high frequencies require greater gain, low frequencies (below $\sim$1 kHz) typically require less. Ambient ocean noise is strongest at low frequencies, and, if amplified too much, can exceed the recorder's dynamic range (a process called "clipping" or "saturation") and render it incapable of resolving anything else. This concern becomes even greater for tag applications, as the "flow noise" of water flowing past the tag usually exceeds ambient sounds at low frequencies when the subject is moving.

As a result of the divergent gain requirements for low and high frequencies, the modified concept incorporates two independent hydrophones and hydrophone channels. A "low-power" channel monitors frequencies below 9.3 kHz over longer durations, and a "high-frequency" channel monitors higher frequencies above $\sim$10 kHz over shorter durations.

Antialias filtering

The low-power channel is intended for general-purpose recording at lower frequencies over durations of days to weeks. Power conservation for such extended deployments dictates that the sampling frequency, and therefore the antialias cutoff frequency, should be adjustable to the minimum necessary for the application. The low-power channel uses adjustable 8^{th}-order elliptic filter hardware whose cutoff frequency varies up to 9.3 kHz depending on the user-selected sample rate.

The high-frequency channel is intended primarily for monitoring odontocete echolocation clicks, and as deployments are expected to be short for these applications, higher power consumption is acceptable. Antialiasing for this channel uses a fixed-frequency 6^{th}-order linear-phase filter that cuts off by -3 dB at 42 kHz but rolls off gradually to -22 dB at 100 kHz.

The selection of a gradual-rolloff linear-phase filter for high-frequency antialiasing resulted from concern that the time-domain structure of echolocation clicks would be unacceptably distorted by more aggressive filtering. Another benefit of linear-phase filtering is that it preserves the quality of the data stream for an optional second pass of filtering that could take place digitally, possibly in real time within the microprocessor, similar to many commercial recording systems.

Primary analog-to-digital conversion

Both low-power and high-frequency channels feed into a single, two-channel 16-bit A/D converter. This A/D converter typically samples either one channel or the other and is not capable of sampling both channels simultaneously; however it does support an alternating "ping-pong" mode in which it switches to the opposite channel before each sample. At high enough sample rates, alternating sampling approximates simultaneous sampling for many applications.

2.1.7 Kinematic sensors and auxiliary data acquisition

3D acceleration (tilt)

While the Bioacoustic Probe's 2D accelerometer provided analog outputs that required sampling with an A/D converter, the Acousonde takes advantage of the recent introduction of digital accelerometers such as ST Microelectronics' LIS302DL. These accelerometers perform A/D conversion internally and provide finished digital samples for reading directly by the microprocessor.

3D compass orientation

Compass orientation is provided by a 3-axis magnetoresistive bridge. The balanced analog output of each of the three bridges is fed to the auxiliary A/D converter. As with any compass, the sensor may become magnetized during use, particularly if magnetic objects are brought close. To counteract this, the device provides, and the Acousonde supports, a set/reset capability to remove magnetization using microsecond-scale current bursts of 1–4 A.

Other channels

A strain-gauge bridge within the pressure transducer provides a balanced analog signal to the auxiliary A/D converter. Temperature and battery voltage round out the suite of auxiliary data sources.

Auxiliary analog-to-digital conversion

Six data signals route to the six-channel auxiliary A/D converter: temperature, battery voltage, three balanced signals from the magnetometer, and one balanced signal from the pressure bridge. The auxiliary A/D converter is a 24-bit sigma-delta converter with integrated buffer and instrumentation amplifier.

2.1.8 Clocking and timekeeping

Two system clocks—one at 32.768 kHz and the other at 13.0 MHz—drive all digital activity within the Acousonde.

The 32.768-kHz clock, referred to as the real-time-clock, operates the date and time electronics embedded within the LPC3180 microprocessor. Provided a battery is present, these electronics maintain the time base even if the rest of the system is turned off or reset. For accurate timekeeping, a low-drift intelligent oscillator sources the 32.768-kHz signal. This oscillator is guaranteed to drift no more than ±1 min/yr for temperatures between 0 and 40 °C. This drift is equivalent to ±2 ppm, an order of magnitude less than the best uncompensated watch crystals. The oscillator maintains this low level of drift using temperature-dependent tuning adjustments every 64 s.

The 13.0-MHz clock, referred to as the main oscillator, drives all electronics other than the date and time system. To provide the best support for multi-unit array applications, an ultra-stable voltage-controlled temperature-compensated crystal oscillator (VCTCXO) sources the 13.0-MHz signal. Voltage control capability allows this oscillator to be adjusted against a reference timebase ("disciplined") for maximum initial frequency accuracy while the built-in temperature compensation keeps the oscillator frequency stable across small temperature changes. While a full characterization of the oscillator's stability was beyond the scope of this project, spot tests have demonstrated drifts of less than one microsecond in an hour, or 0.28 parts per billion.

Unless the application requires the stability of the 13.0-MHz oscillator, it is typically turned off to save power and 13.0-MHz system clocking is sourced instead by the 32.768-kHz clock, multiplied up by a phase-locked loop located within the LPC3180.

2.2 OPERATING SOFTWARE

2.2.1 Operating system (OS)

Several significant changes in hardware architecture necessitated a near-total rewrite of the Bioacoustic Probe's OS for the Acousonde. Among these changes were:

- Migrating processor architecture from the 68000 series to ARM;
- Migrating controller architectures from the Motorola 68EZ328 family to the NXP LPC3000 family;
- Migrating data storage from the Bioacoustic Probe's custom flash filesystem to Microsoft FAT32 on MicroSD cards; and
- Migrating internal data transfers from one-sample-at-a-time to direct-memory-access (DMA) hardware batch transfers.

To support these radical changes within the context of a limited-memory embedded system, OS development adopted the Run-To-Completion (RTC) model based on the "Super Simple Tasker" described by *Samek and Ward* (2006).

An RTC OS is well-suited for data-acquisition systems, being inherently prioritized, event-driven, and conservative with memory. In particular, the event-driven nature of an RTC OS dovetails with the use of DMA hardware; interrupt routines called by the hardware can simply post events and return to the main OS, where the events are delivered to the relevant tasks and those tasks are scheduled based on their priorities.

2.2.2 Dynamic power management

The Acousonde's power needs fluctuate depending on task. Less than 3 mW, for example, suffices to maintain the Acousonde in standby. Sampling at 27 kHz, however, requires 60 mW, and storage of data to the MicroSD card spikes power consumption to 150 mW.* To satisfy these changing power requirements as efficiently as possible demands careful software design.

* Power-draw values are subject to change with future OS revisions.

The OS must identify the level of performance required for a given task and adjust the hardware to provide performance just equal to that required.

The LPC3180 provides several hardware tools to conserve power. In clock throttling, the system clock is sped up or slowed down depending on required performance; the faster the clock, the greater the dynamic power consumption. Dynamic voltage scaling reduces core voltage when the clock is throttled back, magnifying the decrease in power consumption for lower clock speeds. An extreme form of clock throttling is clock gating, in which software enables or disables specific blocks by depriving them of a clock altogether; without a clock, a block's dynamic power draw falls to zero, although static power drain through leakage is still present.

Another primary method of power conservation is reliance on hardware data transfers wherever possible. Like many newer microprocessors, the LPC3180 includes a DMA controller dedicated to automatic data transfer between peripherals and memory. Using DMA will dramatically reduce the system clock speed necessary to perform data-copy tasks that would otherwise require the main processor.

Despite the presence of multiple power-saving features in the Acousonde hardware, the Acousonde OS supports only limited dynamic power management as of this writing. Because of the careful software tuning involved in power management, it is generally considered better to get all of a new instrument's basic functionality operational before attempting to improve power performance. Power management is a key area for future development.

2.2.3 Data filesystem design

Original plans called for the Acousonde to inherit the robust flash filesystem developed for data storage on the Bioacoustic Probe. Switching the data-offload approach from infrared to USB flash-drive emulation partway through the project, however, required that a widely compatible filesystem be used instead so that it would mount properly on the user's personal computer. FAT32 stood out as the obvious, almost unavoidable choice because of its simplicity and ubiquitous PC support.

The revised data-storage approach relies on two separate filesystems. The primary filesystem uses FAT32 on each attached MicroSD card. The auxiliary filesystem, meanwhile, is located on the 256-MB flash chip and uses the original Bioacoustic-Probe custom design. The filesystems are kept separate primarily to avoid multiplexing primary (acoustic data) and auxiliary (kinematic data) writes to the MicroSD cards during high-speed acoustic sampling. Attempting to interleave both data streams to the same card would have significantly complicated maintenance of the FAT32 filesystem and could also have impacted maximum acoustic sampling rate.

When the user boots the Acousonde on a USB cable connected to a personal computer, the OS enters flash-drive emulation mode and makes the FAT32 filesystem available to the user as an external drive. The OS copies auxiliary data from the 256-MB flash chip to the FAT32 filesystem before the drive goes online, allowing the user to access both primary and auxiliary data via USB.

2.3 MECHANICAL REDESIGN

In order to fabricate test units as quickly as possible, the initial mechanical design retained the cylindrical shape of the original Bioacoustic Probe. The project did, however, include a prototyping and mockup effort for an integrated cetacean tag. This monolithic tag would include not only the electronics package but attachment, flotation, and retrieval gear as well, bundled in a single hydrodynamic package. For this part of the effort, the principal investigator teamed with consultants Pat Dexter of Dexter Engineering (mechanical design, design for manufacturability, and encapsulation) and Joe Olson of Cetacean Research Technology (flotation systems and cetacean attachments).

Figure 7 shows the prototype monolithic tag design as of December 2008. The concept consists of a urethane-encapsulated electronics package combined with syntactic-foam flotation, both overmolded by a silicone layer into a single unit. In addition to providing a hydrodynamic surface, the silicone overmolding also includes a single large suction cup for attachment. A receptacle for a third-party VHF retrieval beacon is located in the flotation at the tail end of the package, while the battery housing is located at the leading end of the package; separation of the heavy battery housing as far as possible from the flotation ensures that the package will right itself properly with the beacon's antenna clear of the water. At the close of the project, silicone mockups of the design were produced for evaluation of in-water performance, and four circuit boards were constructed to be ready for assembly of full prototype units.

3 DEVELOPMENT CHALLENGES AND RESULTS

Overall the development effort succeeded well, and the design has proved itself as a fixed recorder in nearshore waters of the Arctic, Atlantic and Pacific Oceans. Many challenges arose during the project, however, extending the development schedule far longer than originally anticipated.

3.1 IMPLEMENTING USB

Of all the surprises during this effort, none was as consequential as SigmaTel's removal of its very-fast-infrared (VFIR) controller from the market in 2007. This event caught the project just as the first prototype boards were headed for manufacturing, and added many months to the schedule.

The switch from infrared data transfer to emulating a USB flash drive required four profound changes in the design. First, USB hardware, including an external controller chip and a USB connector, had to be squeezed onto an already crowded electronics board. Second, the need to accommodate the USB connector into the battery housing required development of a new positive battery spring contact that could coexist with the USB connector within the housing's limited space. Third, USB software had to be implemented, including both a low-level driver and the USB mass-storage class, and this software had to be thoroughly tested for compatibility with USB hosts such as Windows and Mac OS X. Finally, emulation of a

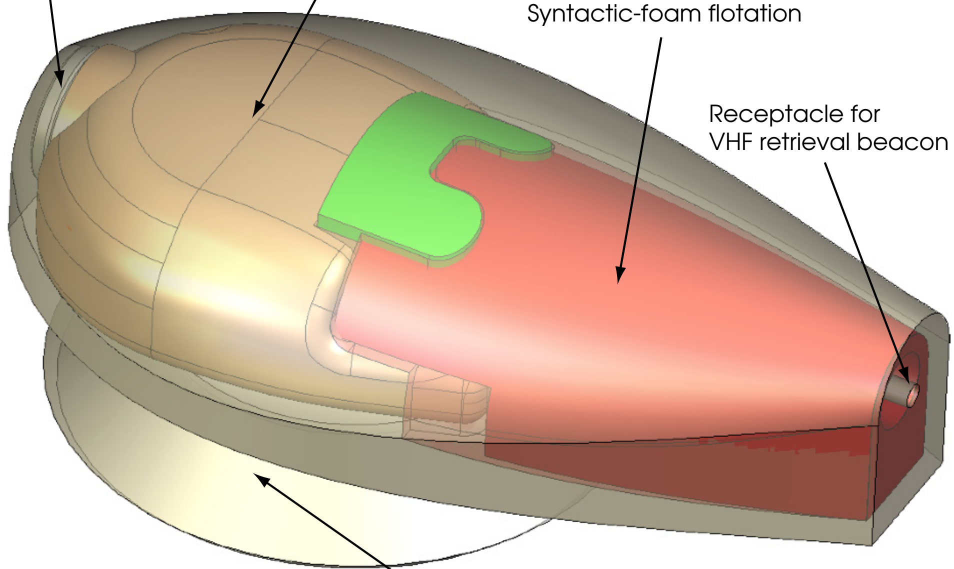

Figure 7. Prototype design for an integrated "monolithic" cetacean tag. The prototype concept involved a hydrodynamic silicone overmold, including a suction cup, covering both the electronics package and the attached flotation.

USB flash drive meant that the Acousonde had to adopt FAT32, a filesystem that is widely supported on personal computers but was not intended for data acquisition systems or for fault tolerance on a battery-operated flash-storage device.

3.2 COMPONENT INTERFACING AND COMPATIBILITY

Two components proved much more difficult to interface with the microprocessor than anticipated.

The acoustic analog-to-digital (A/D) converter, while it had the necessary specifications, would have required extensive "babysitting" by the microprocessor if it had been interfaced according to its application notes. This in turn would have translated to much greater power consumption than desired, as the microprocessor would have had to run with a fast system clock just to program the A/D for each sample. Instead of accepting this tradeoff, a more complex hardware interface was developed to provide the required signaling without processor intervention. This interface has already improved power performance, and may make further improvements possible if the DMA controller can be engaged to transfer data from the A/D in large batches.

The digital accelerometer chosen for this design offered communication with the microprocessor over either of two bus standards, known as SPI and I2C. The design initially adopted I2C. After the first prototype boards were built, however, the LPC3180 microprocessor showed itself to have an incompatibility with the selected accelerometer over I2C when being operated at low system clock speeds. Since reducing system clock speed is key to lower power consumption, the accelerometer interface was redesigned to use SPI.

3.3 CIRCUIT-BOARD LAYOUT

While reducing the Acousonde's power consumption involved lowering voltages and using switching power supplies, these techniques also made its data paths more susceptible to digital self-noise. This battle between reducing power consumption and improving noise performance was largely fought within the circuit board layout.

To defend against digital self-noise, the Acousonde uses a twelve-layer layout with multiple ground and power layers to shield sensitive traces and contain noise radiation. The Acousonde also implements detailed recommendations for low-noise mixed-signal layout made by National Semiconductor during a workshop it sponsored in Santa Clara, California in May 2005 (*National Semiconductor*, 2005). While some of these recommendations run counter to typical design practice, implementing them has yielded excellent results. In one test, a stable DC signal from a on-board voltage reference was wired to the input of the acoustic A/D converter and digitized at a 464-kHz rate. Noise in the digitized data matched the converter's specification, indicating that despite the presence of switching power supplies and a 208-MHz microcomputer a few inches away on the same board, no digital noise leaked into this test data path. While parts of the production data path are more susceptible to interference than the voltage reference, this test nevertheless showed that the layout made a good start.

3.4 MECHANICAL REDESIGN

The prototype hydrodynamic design discussed earlier and shown in Figure 7 satisfied many, but not all, of its technical objectives. These objectives and the degree to which they were accomplished are:

- **Hydrodynamic?** Yes, but tests with a silicone mockup showed that the prototype package tended to migrate downstream, indicating greater drag than desired.
- **Buoyant with the correct orientation when afloat?** Yes.
- **Small and robust?** Not sufficiently small. The prototype design was still too large for application with mid-sized cetaceans.
- **Rapid to prepare in the field?** Yes. The package design seals all components together, obviating the need for any field assembly except insertion of a battery and a VHF retrieval beacon.
- **Configurable?** No. The suction cup and the flotation cannot be replaced without destroying the silicone overmold.

- **Releases with both active and redundant mechanisms?** No active release; insufficient time was available to develop and test an active release mechanism suitable for this mechanical configuration. However the use of a suction cup inherently provides an eventual passive release.

As of this writing, a new hydrodynamic design is underway building on several aspects of the original effort while improving on size, drag, and configurability. This new design is expected to be available in mid-2010 as the Acousonde 3B.

3.5 DEVELOPMENT TRADEOFFS

The many challenges to the original schedule led unavoidably to development tradeoffs. Because the primary function of the Acousonde is acoustic recording, the decision was made to focus on implementing at least basic low-frequency acoustic functionality before anything else. Other subsystems—notably high-frequency acoustic sampling and the kinematic sensors—were tested enough to ensure proper operation, but full functionality had to be postponed. High-frequency sampling in particular was tested in burst mode at a sample rate of 464 kHz to assure that the hardware is capable of satisfying all technical objectives.

3.6 LONG-TERM VIABILITY OF COMMANDING VIA PALM INFRARED

Market share of the Palm personal digital assistant (PDA) has steadily declined with the rise of multifunction "smart" cell phones. In December 2008 Palm CEO Ed Colligan acknowledged that he saw an "inevitable end" to its handheld PDA products:

> *And finally in the handheld business, it continues to sell, it's selling this holiday season, we will push those out into the marketplace as long as there is a sufficient demand. One of the things that's kind of a self-fulfilling prophecy is we're not developing new ones, and so there's an inevitable end. But I think right now we're playing it out, it is a product line that has significant and strong margins, and so we're going to continue to sell them as long as there's demand for those products.*
> —Palm CEO Ed Colligan, December 18, 2008

An inevitable end to the Palm handheld platform means an inevitable end to the use of Palms to command the Acousonde. However, Palm appears committed to continued manufacturing and sales of its handhelds in the near term, and it may be expected that its handhelds will be available through eBay and other avenues even after Palm discontinues the product line.

4 APPLICATIONS/TRANSITIONS

Greeneridge Sciences formally announced the Acousonde 3A for sale on 16 January 2009. The first two commercial units for marine science were delivered to the Monterey Bay Aquarium Research Institute on 25 May 2009, and a paper has already been presented at a meeting of the American Geophysical Union based on data acquired with those units (*Henthorn et al.*, 2009). As of this writing, a total of nine Acousondes have been encapsulated, seven of which have been transitioned for scientific, engineering, or educational use. Table 4 provides a partial list of Acousonde customers and intended applications to date.

The table lists two customers from fields other than protected-species research. This demonstrates the flexibility of the design, but also suggests that the project has the capability to become self-sustaining through broad-based sales.

TABLE 4. Acousonde customers as of January 2010.

Customer	Planned topic*
Dr. Whitlow Au *Hawaii Institute of Marine Biology*	Humpback whales
Mr. John Calambokidis *Cascadia Research* Dr. John Hildebrand *Scripps Institution of Oceanography* Dr. Erin Oleson *NOAA Fisheries*	Blue/fin/humpback whales
Dr. David Caress *Monterey Bay Aquarium Research Institute*	Marine geoacoustics
LCDR Steven Mancini *Naval Postgraduate School*	Tactical oceanography training
Dr. Michael Noad *University of Queensland*	Humpback whales
Dr. Susan Parks *Pennsylvania State University*	Baleen whales
Dr. Aaron Thode *Scripps Institution of Oceanography*	Gray and sperm whales

*In several cases Acousondes are ordered, but not yet delivered.

5 CONCLUSION

Greeneridge Sciences, Inc., has developed a wideband acoustic recording tag, the Acousonde™, under ONR Contract N00014-06-C-0099. The new instrument is designed particularly for attachment to echolocating odontocete whales and dolphins, with acoustic sample rates up to 232 kHz and 3D tilt and compass sensors in addition to standard sensors for temperature and depth. The Acousonde can record 8 GB of data, corresponding to 4.6 hours at the maximum sample rate or 22 days at a 2 kHz sample rate. Users command the instrument by entering the desired sampling program into a Palm personal digital assistant via a graphical user interface, and then sending the program by infrared from the Palm to the Acousonde. After gathering data, when the instrument is attached to a personal computer via USB cable, it behaves as a USB flash drive, and data may be offloaded with an ordinary drag-and-drop or copy operation. Development of the hardware and software took advantage of state-of-the-art power conservation concepts and tools in order to optimize size and performance, but the level of complexity involved together with several unexpected challenges extended the development schedule. The initial mechanical design is commercially available as the Acousonde 3A and is in transition to several customers. For use as a cetacean tag, the Acousonde 3A requires the addition of external attachment, flotation and retrieval systems; however, a complete overhaul of the Acousonde mechanical format has produced a more hydrodynamic one-piece "monolithic" design with integrated attachment and flotation. The monolithic design is being revised now with release planned for mid-2010 as the Acousonde 3B.

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GLOSSARY OF COMPUTER-INDUSTRY TERMINOLOGY

ARM A widely-used microprocessor architecture originally designed in 1983 as the Acorn RISC Machine. Also the corporation, ARM Inc., that owns the intellectual property for ARM processors.

block A subunit of a single-chip microprocessor dedicated to a specific function, such as a real-time clock or a memory controller.

controller Hardware specifically designed to interface a computer with a peripheral device such as memory or an SD card.

core Hardware at the "heart" of a microprocessor that executes software.

DMA Direct Memory Access, a method of copying large amounts of data utilizing special-purpose controller hardware. DMA relieves the core to attend to other tasks or to be idle, improving performance.

driver Software that operates a specific controller or device.

embedded system Any product that, despite incorporating a computer, would not ordinarily be called a computer. Embedded systems are now ubiquitous in automobiles, appliances, and handheld technology.

FAT File Allocation Table, a filesystem format originally co-authored by Bill Gates in 1976–1977. FAT was never intended for portable systems with unreliable power or for memory technologies such as flash that degrade with repeated writes. FAT requires significant programming effort to adapt for these conditions. On the other hand, it is widely compatible with personal computers.

flash The most common solid-state technology for high-capacity non-volatile data storage. Flash memory's major disadvantage is degradation with repeated writes. Filesystems designed around this weakness are called flash filesystems.

operating system (OS) Software that decides what task a computer should perform at any given moment, transfers program execution to that task, and provides the task with access to the computer's hardware. Data acquisition systems require special-purpose operating systems whose architecture guarantees timely performance of urgent tasks.

SD cards SecureDigital cards, flash memory packaged for consumer use.

SDRAM Synchronous dynamic random access memory, a form of general-purpose volatile memory with very high data capacity but relatively poor power efficiency.

SRAM Static random access memory, a form of general-purpose volatile memory that is power-efficient but only available in small capacities.

volatile memory Memory whose contents are lost the moment power is interrupted.